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# AXION SUPERMULTIPLET COSMOLOGY AND LATE BARYOGENESIS[1]

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We show that the implementation of the Peccei–Quinn solution to the strong CP problem within a supersymmetric framework provides naturally a very efficient mechanism for baryogenesis, based on the late decay (at $T \sim$ GeV) of the axion supermultiplet companions, that produce out of equilibrium gluinos. The CP violation in gluino decays combined with B violating couplings that can be present in supersymmetric models can easily give rise to $\eta \sim 10^{-10}$. The most attractive features of this scenario are that the amount of CP violation does not need to be large and that it also works for low reheating temperatures after inflation ($T_{RH} \gtrsim 10^4$ GeV).

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It is well known that the present baryon asymmetry of the universe $\eta \equiv n_B/n_\gamma \simeq 3\times 10^{-10}$, as required for a successful prediction of the light element abundances within the standard nucleosynthesis scenario, can be generated dynamically provided that the three 'Sakharov' conditions are satisfied, i.e. in the presence of $i$) interactions violating B, $ii$) C and CP nonconservation (so that the partial decay rates of particles and antiparticles differ), and $iii$) an out of equilibrium situation, so that $i$) does not lead to the equilibrium value $n_B = 0$.

It is remarkable that these conditions are already satisfied in the Standard Model, in which the anomalous B+L violation is unsuppressed at high temperatures and the non–equilibrium may arise during the (first order) electroweak phase transition, although a value of $\eta$ around $10^{-10}$ is by no means guaranteed and most probably requires the enlargement of the Higgs sector, including further CP violation. GUTs where however the first scenarios to be considered for baryogenesis, since quark–lepton unification naturally leads to B–violating interactions mediated by heavy ($M_X \sim 10^{12} \div 10^{16}$ GeV) bosons and at the corresponding temperatures in the early universe the expansion was fast enough to produce non–equilibrium. Some difficulties for these models are that the anomalous processes acting at temperatures between $M_X$ and $M_W$ would erase any B+L asymmetry, so that the generation of B–L is required in GUTs, and also that there is no guarantee that the reheating temperature after inflation $T_{RH}$ be larger than $M_X$. This problems strongly motivated low temperature baryogenesis scenarios.

Besides the electroweak baryogenesis and some early models based on late out of equilibrium particle decays via B violating channels, a nice theoretical framework for B and CP violation and late decays was found in supersymmetric models. This is because gauge symmetry and supersymmetry allow for B and L violating couplings in the superpotential of the form $\lambda u^c d^c d^c + \lambda' LQe^c + \lambda'' LLe^c$, where $L$ and $Q$ are the lepton and quark doublets while the remaining fields are singlets. Of course the simultaneous presence of all these terms induces unacceptable proton decay, so that some discrete symmetry is usually invoked to ensure proton stability. The different possibilities have been thoroughly studied recently in ref. [1], that divides them in 'R', 'B' and 'L'–parities. R–parity is the most diffused because it minimizes the 'new physics' ($\lambda = \lambda' = \lambda'' = 0$) and leads to very specific signatures for SUSY, but the other two are equally natural and in some respects even preferable (they also forbid dimension 5 $\not{B}$ operators). B–parity requires $\lambda = 0$, allowing for L violation while L–parity allows for B violation ($\lambda' = \lambda'' = 0$). Clearly in the search of sources of B violation one should consider L–parity with $\lambda \neq 0$.

The couplings $\lambda$ involving the first two generations are strongly restricted by $\Delta B = 2$ processes such as heavy nuclei decay and $n - \bar{n}$ oscillations, so that we will assume that just $\lambda_{332}$ (or $\lambda_{223}$) is nonvanishing. These couplings induce many new processes, such as: LSP squark mediated decay $\chi \to qqq$, $\not{B}$ interactions $\chi + q \leftrightarrow \bar{q}\bar{q}$ (that may be dangerous for the subsistence of $n_B \neq 0$ at low temperatures), squark decays ($\tilde{q} \to \bar{q}\bar{q}$) and soft susy breaking terms trilinear in the squark fields that, in conjunction with gaugino masses, are an important source of CP violation.

This framework was first exploited for baryogenesis by Dimopoulos and Hall[2] who found that a two loop interference diagram produced CP violation in squark decays, and that out of equilibrium squarks could be the result of the inflaton decay. To avoid erasing $\eta$ by processes such as $\chi + q \leftrightarrow \bar{q}\bar{q}$ and to allow for nucleosynthesis, the universe temperature just after the decay $T_d$ should satisfy: few GeV $\gtrsim T_d \gtrsim$ MeV. Since in this scenario this temperature was just $T_{RH}$, this imposed a strong constraint on inflation. A second attempt was done by Cline and Raby[3] that found that larger (one loop) CP violation was present in gaugino decays and that a source of out of equilibrium gauginos was the late gravitino decay (at $\tau \simeq M_{Pl}^2/m_{3/2}^3 \sim (10\ \mathrm{TeV}/m_{3/2})^3$sec). For the scenario to work it was required that $m_{3/2} \gtrsim 50$ TeV and that the gravitinos dominate the energy density just before decay, that in turn imposes $T_{RH} > 10^{15}$ GeV, again a strong constraint on inflation. Furthermore, the CP violation introduced also generates a (chromo)electric dipole moment for the quarks at one loop, leading to an EDM for the neutron $d_n$ that in these models is close to the experimental upper-bound $10^{-25}$ e·cm.

Can this situation be improved? Some of the clues at our disposal[4] are: we are in a susy theory, so that naturalness arguments (and gauge coupling unification) suggest that the superpartner masses should be $\sim$ TeV. We need a very weakly coupled particle ($X$) so that it decays late (at few GeV $\gtrsim T_d \gtrsim$ MeV) and, to maximize the CP violation and (s)quark yield, its decay should produce gluinos. If we assume that the coupling for the 2–body decay is suppressed by a heavy scale $F$ and write it as $\alpha_s/(8\pi F)$, the decay temperature results $T_d \simeq (m_X/\mathrm{TeV})^{1.5}(10^{12}\mathrm{GeV}/F)$ GeV, pointing then to $F \sim 10^{12}$ GeV. Hence, what we are looking for is the superpartner of a particle whose coupling to gluons arises at a scale $10^{12}$ GeV, i.e. the superpartners of the axion.

In a supersymmetric theory the axion is in a chiral supermultiplet together with its fermionic partner the *axino* ($\tilde{a}$) and the remaining scalar degree of freedom $s$ is usually referred to as *saxino*. Its coupling to the gluon field strength leads, besides to the well known $agg$ vertex, to $sgg$, $s\tilde{g}\tilde{g}$ and $\tilde{a}\tilde{g}g$ couplings, all proportional to $\alpha_s/(8\pi F)$ in the supersymmetric limit. Concerning the masses, the axion mass is protected by the PQ symmetry and arises only by instanton effects, $m_a \simeq m_\pi f_\pi/F \sim 10^{-3} \div 10^{-5}$ eV (for the astrophysically and cosmologically allowed window $F \sim 10^{10} \div 10^{12}$ GeV), but susy breaking usually leads to important splittings inside the multiplet: soft breaking scalar masses can lead to $m_s \sim m_{3/2}$ while for the axino the situation is more complex[5] since in broken global susy its tree level mass is suppressed ($m_{\tilde{a}} \sim m_{3/2}\sqrt{\frac{m_{3/2}}{M_{Pl}}} \sim$ keV), what makes it a good warm dark matter candidate[6] but in broken supergravity its mass depends on its couplings to the hidden sector, with $m_{\tilde{a}} \sim m_{3/2}$ arising as a natural possibility. So, both saxinos or axinos are good candidates for heavy particles ($m \sim 1 \div 10$ TeV) decaying late (at $T \sim$ GeV) with the production of out of equilibrium gluinos. The subsequent decay $\tilde{g} \rightarrow \tilde{q}\bar{q}$ and in the conjugate channel $\tilde{g} \rightarrow \bar{\tilde{q}}q$, with different rates due to the CP violation, are finally responsible for the generation of $\eta$. We see also that our scenario requires $m_X > m_{\tilde{g}} > m_{\tilde{q}}$.

To finally estimate $\eta$, some words should be said about the (s)axino cosmology. At very high temperatures, these particles are in equilibrium due to processes such as $q\tilde{g} \leftrightarrow q\tilde{a}$ or $q\bar{q} \leftrightarrow gs$, that however decouple at a temperature $T_D \simeq (F/10^{12}\text{GeV})^2 10^{11}$ GeV. So, if there is no inflation or $T_{RH}$ is larger than $T_D$, their number density at decoupling is comparable to that of photons. If one follows their later evolution, it results that they are starting to dominate significantly the energy density (for $F > 10^{11}$ GeV) at $T \sim$ GeV, when they decay. If instead $T_{RH} < T_D$, (s)axinos never reach chemical equilibrium after inflation, but however their interactions allow for their partial regeneration, in an amount $\frac{n_X}{n_\gamma}(T_{RH}) \simeq \frac{T_{RH}}{T_D}$. Putting these things together with the expression for the net baryon number produced per gluino decay as a function of the coupling $\lambda$ and the CP violating phase and relating this last one to the induced $d_n$, one finally gets (taking $m_{\tilde{g}} = 300$ GeV)

$$\eta \sim 3 \times 10^{-6} \lambda^2 \frac{d_n}{10^{-25}\text{e} \cdot \text{cm}} \left[\frac{T_{RH}}{T_D}\right]$$

where the term in square brackets corresponds to the case $T_{RH} < T_D$. From this expression one sees that even $\lambda^2 \sim 10^{-4}$ is enough provided $T_{RH} > T_D$, while for $\lambda \sim 1$ even $T_{RH} \sim 10^4$ GeV can work (for $F \sim 10^{11}$ GeV, for which $T_D \sim 10^9$ GeV). In conclusion, this mechanism is consistent with almost all reasonable reheating temperatures after inflation ($T_{RH} \gtrsim 10^4$ GeV), the $\not{B}$ couplings need not be large, the induced EDM of the neutron may be well below the experimental bound, and also a nice feature is that, although with the introduction of $R$–parity violating couplings the LSP is lost as a dark matter candidate, in this scheme the axion appears naturally to take its role.

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